

A high-throughput screen for identifying channel blockers that selectively distinguish transient from persistent sodium channels.

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The present invention generally relates to screens for identifying channel blockers and, and more particularly, relates to a high-throughput screen for identifying channel blockers that selectively distinguish transient from persistent, or
10 non-inactivating, sodium channels.

Voltage-gated sodium (Na^+) channels are crucial for electrical activity in nerve, muscle and heart cells. They mediate the upstroke of the action potential. It is the action potential that is responsible for electrical transmission in the nervous system, and contractility in the heart and skeletal muscle (Aidley, 1991). For a recent review of Na^+ channel structure and function see Catterall (2000). Generally, under resting conditions Na^+ channels are closed until a stimulus depolarizes the cell to a threshold level. At this threshold Na^+ channels begin to open and subsequently rapidly generate the upstroke of the action potential. Normally during an action potential Na^+ channels open very briefly (one millisecond) and then close (inactivate) until the excitable cell (neuron, myocyte, muscle) repolarizes to its resting potential.
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The above described behavior of voltage-gated Na^+ channels can be understood as follows. Na^+ channels reside in three major conformations or states. The resting or closed state predominates at negative membrane potentials (≤ -60 mV).
25 Upon depolarization, the channels enter the active state and open to allow current

flow. The transition from resting to active states occurs within a millisecond after depolarization to positive membrane potentials. Finally during sustained depolarizations (<1-2 ms), the channels enter a second closed or inactive state. Subsequent re-openings of the channels require a recycling of the channels from the 5 inactive to the resting state, which occurs when the membrane potential returns to negative values. This means that membrane depolarization not only opens sodium channels but also causes them to close even during sustained depolarizations (Hodgkin and Huxley, 1952). Thus normal Na^+ channels open briefly during depolarization and are closed at rest (≤ -60 mV).

10 However, some Na^+ channels may be open under resting conditions at relatively negative membrane potentials and even during sustained depolarization (Stys, 1998; Taylor, 1993). These non-inactivating Na^+ channels generate what is known as a persistent Na^+ current, see Figure 1. Persistent Na^+ channels have these properties because they activate (open) at more negative membrane potentials than 15 normal Na^+ channels and inactivate at more positive potentials (Alonso et al, 1999). This means that these persistent Na^+ channels may be open at membrane potentials as negative as -80 mV (Stys, 1998) and stay open at potentials as positive as 0 mV (Alonso, et al, 1999).

10 The above described unique properties of persistent Na^+ channels are exploited in the assays in accordance with the present invention. These persistent Na^+ channels are thought to be involved in synaptic amplification and modification of spiking behavior and also in the generation of conditions leading to cellular dysfunction (Ragsdale et al, 1998; and Taylor, 1993).

Besides their importance under physiological conditions, Na^+ channels are also important under pathophysiological situations. For example they appear play a role in epileptic seizures, cardiac arrhythmias, and ischemia/hypoxia-induced cardiac and neuronal cell death (Taylor et al, 1997; Ragsdale et al, 1998). Importantly, the 5 persistent Na^+ current appears to play a major role in generating the above mentioned cellular abnormalities (Stys, 1998; Taylor et al, 1997). For example persistent Na^+ current is unregulated in both cardiac and neuronal cells during hypoxia (Saint et al, 1996; Hammarstrom, 1998) and may ultimately lead to overload 10 of cell Na^+ and calcium, conditions leading to cell death (Stys, 1998). Blockers of voltage-gated Na^+ channels have been shown to be effective in ameliorating cellular dysfunctions and death resulting from errant operation of voltage-gated sodium 15 channels (Stys, 1998). However, in many cases these blockers inhibit both the normal (transient) and noninactivating (persistent) Na^+ channels to the same extent. Significant block of normal transient Na^+ channels could seriously compromise cellular and organ function or may even cause death. Thus assuming that the 20 persistent Na^+ current is the therapeutic target, it is important to develop drugs that will block this component of Na^+ current but not the normal transient. However, in order to discern whether a compound selectively blocks the persistent over the transient Na^+ current conventional electrophysiological methods such as whole cell patch clamping or voltage clamping in oocyte preparations must be performed (Marty and Neher, 1995; Shih et al, 1998).

Although voltage clamp methods give detailed information about transient and persistent Na^+ currents only a relatively few compounds can be tested using these

conventional electrophysiological techniques. Drug discovery programs trying to find highly selective blockers of the persistent Na^+ current are therefore in need of a rapid high throughput screen that will facilitate the testing of large numbers of compounds simultaneously. Until now no such screen exists.

5 SUMMARY OF THE INVENTION

A method for identifying a Na^+ channel blocker in accordance with the present invention generally includes providing a cell containing a Na^+ channel blocker. The channel blocker demonstrate both a transient and a persistent current. The cell includes a potassium (K) channel and a Na/K AtPase (Na^+ pump). A 10 fluorescent dye is disposed into the well. The fluorescent dye is sensitive to change in cell membrane potential in order to enable optical measurement of cell membrane potential. A Na^+ channel blocker, to be assayed, screened or otherwise identified, is added to the well and a stimulation current is passed through the cell in an amount sufficient to generate an action potential before and after the addition of the Na^+ 15 channel blocker. Thereafter, a change in cell membrane potential is optically measured.

Apparatus in accordance with the present invention includes a screen for identifying a Na^+ channel blocker. The screen includes at least one cell comprising a Na^+ channel, the channel demonstrating both transient and a persistent current. In 20 addition, the cell further comprises a potassium (K) channel and a Na/K ATPase (Na^+) pump. At least one well for containing the cell is provided. A fluorescent dye sensitive to change in cell membrane potential in order to enable optical measurement of cell membrane potential is also included. Electrodes disposed in the well are

in the well are provided for passing a stimulating current through said cell sufficient to generate an action potential before and after the addition of the Na^+ channel blocker, to be identified, to said cell.

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BRIEF DESCRIPTION OF THE DRAWINGS

The advantages and features of the present invention will be better understood with the following detailed description when considered in conjunction with the accompanying drawings of which:

10 Figure 1 is a plot of current vs. time for voltage-gated Na^+ channels upon sustained depolarization showing a combination of inactivating Na^+ channel showing a combination of inactivating Na^+ channels transient current and non-inactivating Na^+ channel persistent current;

15 Figure 2 is a representation of a genetically engineered cell, containing sodium channels that exhibit both transient and persistent currents, enabling a depolarization assay. The engineered cell contains K channels (denoted by gK for K conductance), Na^+ channels exhibiting normal transient ($g\text{Na}$) and noninactivating/persistent ($g\text{Na}_{\text{persistent}}$) currents and a Na^+ pump that maintains the cellular ion gradients. For optimal sensitivity the K conductance (gK) and persistent 20 Na^+ conductance ($g\text{Na}_{\text{persistent}}$) should be similar (order of magnitude). $gK \approx g\text{Na}_{\text{persistent}}$ These cells will be plated in wells and suspended in Na-free media. Concentrated KCl is first added to the wells (see text) to induce a small

depolarization. This is followed by the addition of NaCl to the wells and will cause a further depolarization as Na^+ moves through open persistent Na^+ channels;

Figure 3 is a representation similar to Figure 2 of a cell enabling a depolarization assay. The engineered cell contains K channels (denoted by gK for K conductance), Na^+ channels exhibiting normal transient (gNa) and noninactivating/persistent ($gNa_{\text{persistent}}$) currents and a Na^+ pump that maintains the cellular ion gradients. In this case $gK = gNa_{\text{persistent}}$ (equal conductance). Thus the membrane potential should be near midway the equilibrium (Nernst) potential for K (E_K) and Na^+ (E_{Na}). Assuming cell and media K and Na^+ concentrations of 140 and 20 and 2 and 80 mM respectively $E_K = -107\text{mV}$ and $E \text{Na}^+ = 35\text{ mV}$. Thus the resting membrane potential will be near -36 mV . Upon blockage of persistent Na^+ channels E_m will hyperpolarize towards E_K (theoretically by as much as 70 mV);

Figure 4 is a representation of a cell similar to Figures 2 and 3 enabling a secondary depolarization following ouabain addition. The engineered cell contains K channels (denoted by gK for K conductance), Na^+ channels exhibiting normal transient (gNa) and noninactivating/persistent ($gNa_{\text{persistent}}$) currents and a Na^+ pump that maintains the cellular ion gradients. In this case $gK \gg gNa_{\text{persistent}}$. Addition of ouabain will result in a small depolarization followed by a much larger secondary depolarization. In the absence of a significant Cl conductance or in Cl-free media Na^+ gained via persistent Na^+ channels can not be removed by the Na^+ pump therefore the cell gains Na^+ in exchange for K. As the cell loses K E_K becomes more positive and the cell depolarizes. Blockers of persistent Na^+ channels will prevent the secondary depolarization; and

Figure 5 is a representation of a 96-386 well plate suitable for use in the present invention showing a pair of electrodes disposed in each well.

DETAILED DESCRIPTION

The present invention uses a genetically engineered cell containing appropriate subtype of Na^+ channel, i.e., one that demonstrates both a transient and persistent current. Such a cell can be engineered by incorporating a cDNA for a Na^+ channel with the appropriate biophysical properties into cell type that does not normally contain channels of this type. The cDNAs for several families of Na^+ channels have been cloned and sequenced (for reviews see Goldin, 1999; Catterall, 2000). These cDNAs may be introduced into cell lines by well known molecular biological methods (Sambrook and Russell, 2000). In addition, cell lines that endogenously express Na^+ channels with the appropriate properties can be used and are included in the present invention. The cell may also contain a potassium (K) channel and a Na/K ATPase (Na^+ pump). A 96-386 well plate assay system 10 may be used in conjunction an optical system 20 using well known methods to measure membrane potential (see Figure 5). Fluorescent dyes have been widely used to monitor membrane potential within neuronal and other cell types (Grinvald et al., 1988; Lowe, 1988). The voltage-sensitive dye will be required to have high sensitivity and respond very rapidly to changes in membrane potential such as those generated during an action potential (Gonzalez et al 1995; 1997). A fast ratiometric voltage-sensitive fluorescence dye based on resonance energy transfer (FRET) as described in US patents 5,662035 and 6,107,066 could be used for such an assay. The actual specifics of the invention will be described below in detail.

With reference to Figure 1, there is shown is a current record of a HEK-293 cell containing transected Type III Na^+ channels. These channels are known to generate both persistent and transient Na^+ currents. The cell was patch clamped in the whole cell configuration and depolarized from a holding potential of -80 to -10 mV. The record shows both transient and persistent current components. A rapidly decaying current is followed by a sustained persistent Na^+ current as described in the text.

Figure. 2 is a representation of a genetically engineered cell containing sodium channels that exhibit both transient and persistent currents. In addition the cell contains K channels and Na^+ pumps. A major requirement of the assay in accordance with the present invention is that the potassium conductance (gK) be of the appropriate magnitude such that addition of K to a bath containing the cell to cause a measurable depolarization. In addition, following activation, the conductance of the persistent component of the Na^+ channel ($g\text{Na}_{\text{persistent}}$) must be large enough to produce a voltage change when extracellular Na^+ is introduced into a Na-free assay medium.

To begin the present assay the engineered cells are plated onto the wells 12 of the 96-386 well assay plate 10. The cells are in a Na-free physiological buffer that for example, can contains in mM: 135 NMDG (N-methyl-d-glucamine)Cl, 5 KCl, 2.0 CaCl₂, 1.5 mM MgCl₂ and 20 mM Hepes pH adjusted to 7.4. The first addition to the wells will be a concentrated stock of KCl to elevate the K concentration enough to induce a small (10 mV or more) depolarization thus activating Na^+ channels. However, in the absence of extracellular Na^+ no additional depolarization will be

seen. Within a few milliseconds following K addition the transient Na^+ channels will activate and then inactivate yet the channels generating the persistent Na^+ current will remain open.

Since there is no extracellular Na^+ (NMDG $^+$ substitutes for Na) and NMDG 5 does not permeate Na^+ channels no depolarization will occur. However, following addition of a concentrated stock of NaCl to the wells, the open Na^+ channels that generate the persistent current should cause the membrane to depolarize. The magnitude of the depolarization will depend on the concentration of Na^+ added to the bath and the relative conductance of the Na^+ channels generating the persistent 10 current. The larger the depolarization the easier it will be to perform reliable dose responses with compounds of interest.

The present assay therefore allows one to discover compounds that block the persistent Na^+ current and as such is a screen for persistent Na^+ channels. However, the assay does not address whether compounds that are found to block persistent Na^+ 15 channels also block Na^+ channels generating the transient current. As will be hereinafter described how a parallel assay will discern whether compounds found to block persistent sodium current in the above described assay also block transient Na^+ current generated by typical Na^+ channels.

Figure 3 is a variation of the cell represented in Figure 2 to be used to screen 20 blockers of persistent Na^+ channels. This assay takes advantage of the fact that persistent Na^+ channels are open at relatively negative membrane potentials as described previously (Stys, 1998). In this case the cell is engineered with K and Na^+ channels such that the relative conductance of the K channel and the portion of the

Na^+ channels generating the persistent current are very similar. This will make the resting membrane potential lie approximately halfway between the equilibrium potential (Nernst) potential for Na^+ and that of K (-40 to -20 mV). Under these conditions blocking noninactivating Na^+ channels (these remain open) will 5 hyperpolarize the membrane towards the equilibrium potential for K . Total block of persistent Na^+ channels could result in a significant hyperpolarization, as much as 50 to 60 mV (depending on the equilibrium potentials for Na^+ and K). In this case only one addition need be made and concerns about changes in cell volume due to 10 changes in osmolarity (no concentrated stocks of KCl or NaCl will be added) are of no consequence since drug concentrations will be in the micromolar range. This screen should allow detection of agents that block persistent Na^+ current generated by noninactivating Na^+ channels.

Figure 4 shows the final variation of a cell for detecting blockers of persistent Na^+ channels in a high throughput screen. In this engineered cell there are K 15 channels, voltage gated Na^+ channels, containing a portion whose current is persistent, and a ouabain-sensitive Na/K ATPase (Na^+ pump). In this case the $g\text{K} >> g\text{Na}_{\text{persistent}}$. This means that the resting membrane potential will be near E_{K} .

To start the assay, ouabain is added to the bath in order to block the Na^+ pump. This will lead to a small depolarization (due to blockage of the electrogenic 20 Na^+ pump) and a large secondary depolarization. This secondary depolarization is the key to the assay and relies on the fact that the equilibrium potential for K will become more positive. The rationale is as follows. Following ouabain addition, the cell will gain Na^+ via persistent Na^+ channels that are open at near resting

membrane potential. In the absence of a Cl conductance (or in a Cl free medium) the Na⁺ gained by the cell will be electrically compensated for by an equimolar loss of K. Since the relative gK is large millimolar loss K will result in a depolarization as its Nernst potential becomes more positive. The extent of the depolarization will 5 depend on the amount of Na⁺ gained and thus K lost by the cell following the addition of ouabain. Compounds that block the persistent Na⁺ channels will prevent this depolarization and do so in a dose-dependent manner.

Any of the above methods will allow identification of compounds that inhibit noninactivating/persistent Na⁺ channels. However, it is possible that these 10 compounds may also block the channels generating transient Na⁺ currents. Thus the second part of the screen in accordance with the present invention addresses how compounds that preferentially block persistent but not transient Na⁺ channels can be distinguished.

With reference to Figure 5 a well plate 10 includes wells 12 each containing a 15 pair of silver/silver chloride or platinum electrodes 14, 16 in order to pass a stimulating current sufficient in magnitude to generate an action potential in the engineered cells discussed previously. The use of a fast voltage sensitive dye (FRET) as described above, enables an optical system 20 to measure membrane potential. Using this current passing method, (field stimulation), action potentials may be 20 generated at will before and after the presence of a Na⁺ channel blocker shown to inhibit persistent Na⁺ channels. A dose response may then be performed to observe if the drug in question blocks the action potential and therefore a significant portion

of the transient Na^+ current. In this way drugs that preferentially block persistent transient Na^+ channels may be discovered in a rapid high throughput format.

Specific Na^+ channels blockers like TTX that do not discriminate very well between transient and persistent Na^+ channels are expected to inhibit both channels 5 to nearly the same extent. On the other hand it should be observed that drugs such as lidocaine and mexilitine block persistent Na^+ currents/channels at concentrations that have no effect on transient Na^+ channels and therefore have no effect on action potentials.

These assays can be performed using robotic systems (not shown) that are 10 frequently used for high throughput screens in the pharmaceutical industry. The chances for discovering novel compounds that block or modify persistent Na^+ currents while sparing transient Na^+ currents should be measurably increased. Compounds that are selected by the above screens may then be examined in great 15 detail using conventional electrophysiological methods for further examination and ultimate selection of a lead structure.

References

All of the following references are to be incorporated into the present application for the purpose of further describing certain procedures and properties set forth in this application which are well known in the art.

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Aidley, D.J. (1991). *The Physiology of Excitable Cells.* Third Edition. Cambridge University Press.

Catterall, WA. (2000). From ionic currents to molecular mechanisms: The structure

10 and function of voltage-gated sodium channels. *Neuron*, 26: p 13-25.

Goldin, A.L. (1999). Diversity of mammalian voltage-gated sodium channels. *Ann N Y Acad Sci.*, 868:38-50

15 Gonzalez, J. and Tsien R. (1997). Improved indicators of cell membrane potential that use fluorescence resonance energy transfer. *Chemistry and Biology* 4: p269-277.

Gonzalez, J. and Tsien R. (1995). Voltage sensing by fluorescence resonance

20 energy transfer in single cells. *Biophysical Journal* 69: p 1272-1280.

Hammarstrom, A.K.M. and Gage, P.W. (1998). Inhibition of oxidative metabolism increases persistent sodium current in rat CA1 hippocampal neurons. *Journal of Physiology* 510.3: p 735-741.

5 Hodgkin, A.L. and Huxley, A.F. (1952). A quantitative description of membrane current and its application to conduction and excitation in nerve. *The Journal of Physiology* 117: p500-544.

10 Ju, Y.K. , Saint, D.A. and Gage, P.W. (1996). Hypoxia increases persistent current in rat ventricular myocytes. *Journal of Physiology* 497.2: p 337-347.

15 Magistretti, J. and Alonso, A. (1999). Biophysical properties and slow voltage-dependent inactivation of sustained sodium current in entorhinal cortex layer II principle neurons. A whole cell and single channel study. *Journal of General Physiology* 114: p 491-509.

Sambrook, J. and Russell D. (2000) Molecular cloning – A laboratory manual, 3rd ed., Cold Spring Harbor Press, Cold Spring Harbor, NY

20 Marty, A. and Neher, E. (1995). Tight-seal Whole-cell recording. In: *Single Channel Recording*. Sakmann, B., and Neher, E. Editors. 1995. Plenum Press, New York.

Ragsdale, D.S. and Avoli, M. (1998). Sodium channels as molecular targets for antiepileptic drugs. *Brain Research Reviews* 26: p 16-28.

Shih, T.M., Smith, R.D., Toro, L., and Goldin, A.L. (1998). High level expression 5 and detection of ion channels in *Xenopus* oocytes. *Methods in Enzymology* 293: p529-556.

Stys, P. (1998). Anoxic and ischemic injury of myelinated axons in the CNS white matter: From mechanistic concepts to therapeutics. *Journal of Cerebral Blood Flow and Metabolism*. 18: p 2-25. 10

Taylor, C.P. (1996). Voltage-gated sodium channels as targets for anticonvulsant, analgesic, and neuroprotective drugs. *Current Pharmaceutical Design* 2: p 375-388.

15 Taylor, C.P. and Narasimhan, L.S. (1997). Sodium Channels and Therapy of Central Nervous System Diseases. *Advances in Pharmacology* 39: p 47-98.

Taylor, C.P. (1993). Na^+ currents that fail to inactivate. *Trends in Neuroscience* 16: p 455-460.

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Although there has been hereinabove described a method and screen for identifying a Na^+ channel blocker, in accordance with the present invention, for the purposes of illustrating the manner in which the invention may be used to advantage,

it will be appreciated that the invention is not limited thereto. Accordingly, any and all modification, variations or equivalent arrangements which may occur to those skilled in the art should be considered to be within the scope of the invention as defined in the appended claims.